METHOD AND APPARATUS FOR PLANARIZING MICROELECTRONIC WORKPIECES

TECHNICAL FIELD

[0001] The present disclosure relates to planarizing microelectronic workpieces using chemical-mechanical planarization or mechanical planarization in the fabrication of microelectronic devices. Although the present invention is related to planarizing many different types of microelectronic workpieces, the following disclosure describes particular aspects with respect to forming Shallow Trench Isolation (STI) structures.

BACKGROUND

[0002] Mechanical and chemical-mechanical planarizing processes (collectively "CMP") remove material from the surface of semiconductor wafers, field emission displays or other microelectronic substrates in the production of microelectronic devices and other products. Figure 1 schematically illustrates a CMP machine 10 with a platen 20, a carrier assembly 30, and a planarizing pad 40. The CMP machine 10 may also have an under-pad 25 attached to an upper surface 22 of the platen 20 and the lower surface of the planarizing pad 40. A drive assembly 26 rotates the platen 20 (indicated by arrow F), or it reciprocates the platen 20 back and forth (indicated by arrow G). Since the planarizing pad 40 is attached to the under-pad 25, the planarizing pad 40 moves with the platen 20 during planarization.

[0003] The carrier assembly 30 has a head 32 to which a substrate 12 may be attached, or the substrate 12 may be attached to a resilient pad 34 in the head 32. The head 32 may be a free-floating wafer carrier, or an actuator assembly 36 may be coupled to the head 32 to impart axial and/or rotational motion to the substrate 12 (indicated by arrows H and I, respectively).

[0004] The planarizing pad 40 and a planarizing solution 44 on the pad 40 collectively define a planarizing medium that mechanically and/or chemically removes material from the surface of the substrate 12. The planarizing pad 40 can be a soft pad or a hard pad. The planarizing pad 40 can also be a fixed-abrasive planarizing pad in which abrasive particles are fixedly bonded to a suspension material. In fixed-abrasive applications, the planarizing solution 44 is typically a non-abrasive "clean solution" without abrasive particles. In other applications, the planarizing pad 40 can be a non-abrasive pad composed of a polymeric material (*e.g.*, polyurethane), resin, felt or other suitable materials. The planarizing solutions 44 used with the non-abrasive planarizing pads are typically abrasive slurries with abrasive particles suspended in a liquid.

[0005] To planarize the substrate 12 with the CMP machine 10, the carrier assembly 30 presses the substrate 12 face-downward against the polishing medium. More specifically, the carrier assembly 30 generally presses the substrate 12 against the planarizing liquid 44 on a planarizing surface 42 of the planarizing pad 40, and the platen 20 and/or the carrier assembly 30 move to rub the substrate 12 against the planarizing surface 42. As the substrate 12 rubs against the planarizing surface 42, material is removed from the face of the substrate 12.

[0006] CMP processes should consistently and accurately produce a uniformly planar surface on the substrate to enable precise fabrication of circuits and photo-patterns. During the construction of transistors, contacts, interconnects and other features, many substrates develop large "step heights" that create highly topographic surfaces. Such highly topographical surfaces can impair the accuracy of subsequent photolithographic procedures and other processes that are necessary for forming sub-micron features. For example, it is difficult to accurately focus photo patterns to within tolerances approaching 0.1 micron on topographic surfaces because sub-micron photolithographic equipment generally has a very limited depth of field. Thus, CMP processes are often used to

transform a topographical surface into a highly uniform, planar surface at various stages of manufacturing microelectronic devices on a substrate.

[0007] In the highly competitive semiconductor industry, it is also desirable to maximize the throughput of CMP processing by producing a planar surface on a substrate as quickly as possible. The throughput of CMP processing is a function, at least in part, of the polishing rate of the substrate assembly and the ability to accurately stop CMP processing at a desired endpoint. Therefore, it is generally desirable for CMP processes to provide a controlled polishing rate (a) across the face of a substrate to enhance the planarity of the finished substrate surface, and (b) during a planarizing cycle to enhance the accuracy of determining the endpoint of a planarizing cycle.

[0008] One concern of CMP processing is that it is difficult to control the polishing rate. The polishing rate typically varies across the surface of the workpiece or during a planarizing cycle because (a) topographical areas with high densities of small features may polish faster than flat peripheral areas, (b) the distribution of abrasive particles in the slurry varies across the face of the workpiece, (c) velocity and thermal gradients vary across the surface of the workpiece, (d) the condition of the surface of the planarizing pad varies, (e) the topography of the workpiece changes, and (f) several other factors. The variance in the polishing rate may not be uniform across the workpiece, and thus it may cause different areas on the workpiece to reach the endpoint at different times. This produces over-polishing in areas with high polishing rates, and under-polishing in other areas with lower polishing rates.

[0009] The variance in the polishing rate can be particularly difficult to control when slurries with very small abrasive particles are used on wafers with a high density of small features. It is becoming increasingly important to use very small abrasive particles in CMP slurries because the feature sizes of the microelectronic components are decreasing to produce high performance/capacity products, and the small particle sizes enable mechanical removal of material from workpieces without damaging or otherwise impairing the small components. The

slurries with small particle sizes, however, may produce different results as the surface of the planarizing pad changes throughout a run of workpieces, or even during a single planarizing cycle of one workpiece. This can produce inconsistent results that reduce the reliability of CMP processing. Therefore, there is a strong need to provide a planarizing process that can accurately endpoint a planarizing cycle without significantly increasing the time to planarize each workpiece.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Figure 1 is a schematic cross-sectional view of a planarizing machine in accordance with the prior art.

[0011] Figure 2 is a schematic cross-sectional view of a planarizing machine in accordance with an embodiment of the invention.

[0012] Figures 3A-3D are cross-sectional views showing a portion of a planarizing machine and a microelectronic workpiece at various stages of a planarizing cycle in accordance with a method of the invention.

[0013] Figure 4 is a schematic cross-sectional view of a planarizing machine in accordance with another embodiment of the invention.

[0014] Figure 5 is a schematic cross-sectional view of a planarizing machine in accordance with yet another embodiment of the invention.

DETAILED DESCRIPTION

[0015] The following disclosure describes several planarizing machines and methods for accurately planarizing microelectronic workpieces. Several embodiments of the planarizing machines produce a planar surface at a desired endpoint in the microelectronic workpieces by (a) initially removing material from the surface of the workpiece using a first planarizing medium that quickly removes topographical features but has a low polishing rate on planar surfaces; and (b) subsequently removing material from the surface of the workpiece using a second planarizing medium that has a higher polishing rate on planar surfaces than the first polishing medium. Several embodiments of the following planarizing

machines and methods for planarizing microelectronic workpieces accordingly form a planar surface across a workpiece at a desired endpoint in a relatively short period of time. Figures 2-5 illustrate several embodiments of planarizing machines and methods in accordance with the invention, and like reference numbers refer to like components throughout these figures. Many specific details of certain embodiments of the invention are set forth in the following description and Figures 2-5 to provide a thorough understanding of such embodiments. A person skilled in the art will thus understand that the invention may have additional embodiments, or that the invention may be practiced without several of the details described below.

[0016] Figure 2 is a schematic view of a planarizing machine 100 in accordance with one embodiment of the invention. In this embodiment, the planarizing machine 100 includes a first plate 120a, a second plate 120b, and a separate drive system 122 coupled to each of the plates 120a-b. The plates 120a-b can be separate platens, and each drive system 122 can independently rotate the plates 120a-b. The drive systems 122 can be coupled to a monitor 124 that senses the loads on each drive system 122. The monitor 124, for example, can be a current meter that measures the electrical current drawn by motors in the drive systems 122. As explained in more detail below, the monitor 124 is used to estimate the status of the surface of a workpiece being planarized on the planarizing machine 100.

[0017] The planarizing machine 100 can also include a first planarizing medium 130a and a second planarizing medium 130b. The first planarizing medium can include a first pad 140a on the first plate 120a. The first pad 140a has a first planarizing surface 142a upon which an abrasive planarizing slurry (not shown in Figure 2) is disposed. The second planarizing medium 130b includes a second pad 140b on the second plate 120b. The second pad 140b can have a second planarizing surface 142b upon which the same planarizing slurry or another abrasive planarizing slurry is disposed. The first planarizing surface 142a has a first roughness, and the second planarizing surface 142b has a second

roughness. The first roughness of the first planarizing surface 142a is greater than the second roughness of the second planarizing surface 142b. The first planarizing surface 142a, for example, can have a first texture and the second planarizing surface 142b can have a second texture such that the second planarizing surface 142b removes material from a planar surface of a microelectronic workpiece faster than the first planarizing surface 142a. As explained in more detail below, the different textures or roughnesses between the first and second planarizing surfaces 142a and 142b enables the planarizing machine to more effectively remove material from a workpiece in a controlled manner at different stages of a planarizing cycle.

[0018] The planarizing machine 100 can also include a workpiece carrier 150 having a drive mechanism 152, an arm 154 coupled to the drive mechanism 152, and a holder 156 carried by the arm 154. The holder 156 is configured to hold and protect a microelectronic workpiece 160 during a planarizing cycle. The workpiece carrier 150 can accordingly rotate the arm 154 to position the holder 156 at either the first pad 140a or the second pad 140b. Additionally, the workpiece carrier 150 can raise/lower or rotate the holder 156 to impart the desired relative motion between the workpiece 160 and the planarizing media 130a and 130b. Suitable workpiece carriers 150 are used in existing rotary CMP machines manufactured by Applied Materials, Incorporated.

[0019] The planarizing machine 100 can further include a computer 170 that is operatively coupled to the drive systems 122 and the monitor 124 by lines 172, and operatively coupled to the workpiece carrier 150 by a line 174. The computer 170 contains a computer-readable medium, such as software or hardware, that executes instructions to carry out a number of different methods for planarizing a workpiece 160 on the first planarizing medium 130a during a first abrasive stage of a planarizing cycle and then the second planarizing medium 130b during a second abrasive stage of the planarizing cycle. In general, the computer 170 causes the workpiece carrier 150 to press the workpiece 160 against the first planarizing surface 142a and a slurry containing abrasive particles during the first

abrasive stage of the planarizing cycle, and then move the workpiece 160 and press it against the second planarizing surface 142b in the presence of a slurry containing abrasive particles during the second abrasive stage of the planarizing cycle. The first abrasive stage of the planarizing cycle can be used to remove topographical features on the surface of the workpiece 160 in a manner that forms a surface that is at least approximately planar, and then the second abrasive stage of the planarizing cycle can be used to remove material from a planar surface on the workpiece 160 at a higher polishing rate than the polishing rate of the first planarizing medium 130a. It will be appreciated that the computer 170 can contain instructions to perform several different types of methods using the abrasive planarizing media 130a and 130b in accordance with several different embodiments of the present invention.

[0020] Figures 3A-3D illustrate progressive stages of planarizing a microelectronic workpiece 160 in accordance with an embodiment of a method of the invention. Several embodiments of the planarizing machine 100 described above with reference to Figure 2 can be used to planarize the microelectronic workpiece 160 in accordance with this method. It will be appreciated, however, that the planarizing machine 100 can be used to planarize microelectronic workpieces using methods in accordance with other embodiments of the invention. The methods described below with reference to Figures 3A-3D can also be performed using alternate embodiments of planarizing machines in accordance with the invention described with reference to Figures 4 and 5.

[0021] Figure 3A illustrates the microelectronic workpiece 160 at an initial period of a first abrasive stage of a planarizing cycle. The microelectronic workpiece 160 shown in Figure 3A has a Shallow Trench Isolation (STI) structure including a substrate 162, a plurality of trenches 163 in the substrate 162, a polish-stop layer 164 on the top surfaces of the substrate 162, and a fill layer or cover layer 165. The fill layer 165 typically has a plurality of high points or peaks 166 over the segments of the polish-stop layer 164 and a plurality of troughs 167 over the trenches 163. During the initial period of the first abrasive stage, the method

includes removing material from the microelectronic workpiece 160 by pressing the workpiece 160 against the first planarizing surface 142a and an abrasive slurry 144 on the first planarizing surface 142a. The abrasive slurry 144, for example, can include a liquid solution and a plurality of small abrasive particles 145. The abrasive particles 145 can be particles of ceria, alumina, titania or other materials having an average particle size of approximately 0.1-100 nm. It will be appreciated that other types of particles having other particles sizes can be used as well in accordance with other embodiments of the invention. The first surface 142a has a texture defining a first roughness that is relatively high compared to the second surface 142b of the second pad 140b. The first surface 142a and the abrasive slurry 144 work together to remove the peaks 166 rather quickly. The removal of the peaks 166 accordingly reduces the topographical variances across the surface of the workpiece 160 until the planarizing surface 142a begins to engage the troughs 167. At this point, the planarizing surface 142a begins to remove material from an over-burden region "*O*" of the fill layer 165.

[0022] Figure 3B illustrates a subsequent period of the first abrasive stage of a method for planarizing the workpiece 160. At this period, the peaks 166 (Figure 3A) have been removed such that the fill layer 165 has a intermediate surface 168 that is in the overburden region *O*. The intermediate surface 168 is generally at least approximately planar at this period of the first abrasive stage. The inventors have discovered that the combination of the relatively rough first planarizing surface 142a and the abrasive slurry 144 having small abrasive particles has a very low polishing rate on the substantially planar intermediate surface 168. The polishing rate can be low enough such that the intermediate surface 168 acts as a virtual polish-stop surface in the overburden region *O* when it becomes planar or nearly planar.

[0023] The termination of the first abrasive stage shown in Figure 3B can be identified by the monitor 124 (Figure 2) and the computer 170 (Figure 2). The onset of planarity typically causes an increase in the drag force exerted by the workpiece 160 against the first pad 140a. The increase in drag force increases

the load on the drive system 122 (Figure 1), which causes the drive system 122 to draw more electricity to operate the motor that rotates the plate 120a. The monitor 124 measures such an increase in the current draw and sends a signal to the computer 170. When the current draw reaches a predetermined level or increases in a predetermined manner, the computer 170 indicates that the intermediate surface 168 of the workpiece 160 is at least approximately planar in the overburden region *O*.

[0024] Figure 3C illustrates an initial period of a second abrasive stage for planarizing the workpiece 160 using the planarizing machine 100. At the initial period of the second abrasive stage, the method includes removing additional material from the workpiece 160 by pressing the workpiece 160 against the second planarizing surface 142b and an abrasive slurry 144. The second planarizing surface 142b has a second roughness that is less than the first roughness of the first planarizing surface 142a. The "smoother" second planarizing surface 142b and the abrasive slurry 144 (not shown in Figure 3C) operate together to have a higher polishing rate on the substantially planar intermediate surface 168 than the polishing rate of the first planarizing surface 142a. The second abrasive stage of the planarizing cycle accordingly removes the material in the overburden region *O* of the fill layer 165 at an adequate polishing rate to enhance the throughput of the planarizing cycle.

[0025] Figure 3D illustrates a subsequent period of the second abrasive stage at which the polish-stop layer 164 endpoints the planarizing cycle. The polish-stop layer 164 has a much lower polishing rate than the fill layer 165, and thus the polish-stop layer 164 inhibits further removal of material from the workpiece. The polish-stop layer 164, for example, can be a silicone nitride layer (Si_3N_4) and the fill layer 165 can be a silicone oxide.

[0026] The planarizing machine 100 can sense the endpoint of the planarizing cycle based on the different coefficients of friction between the polish-stop layer 164 and the fill layer 165. The drag force between the workpiece 160 and the second pad 140b accordingly changes as the polish-stop layer 164 is exposed to

the second planarizing surface 142b. The monitor 124 can sense such a change in the drag force between the workpiece 160 and the pad 140b at the onset of the endpoint, and then computer 170 can terminate the planarizing cycle when the signal from the monitor 124 indicates that the surface of the workpiece is within the polish-stop layer 164.

[0027] Several embodiments of the planarizing machine 100 and the method shown in Figures 2-3D are expected to provide a uniform surface across the face of a workpiece at a desired endpoint without over-polishing or under-polishing. By using a rough planarizing surface for the first abrasive stage, the planarizing cycle can quickly remove the topographical features to an intermediate surface in the overburden region *O* of the workpiece. The removal rate of the topographical features using the rough first planarizing surface is generally about as fast as removing the features with a smooth planarizing surface. However, when the intermediate surface of the workpiece is at least substantially planar, the polishing rate drops significantly using the rough planarizing medium. This allows the planar regions of the workpiece to planarize at a slower polishing rate than the topographical regions so that a planar surface is formed on the substrate in the overburden region *O* without over- or under-polishing particular regions of the workpiece. The second abrasive stage of the planarizing cycle is used to more effectively remove the material from the planar surface in the overburden region *O*. This is possible because the lower degree roughness of the second planarizing surface actually has a higher polishing rate on planar workpiece surfaces using an abrasive slurry than does the higher roughness of the first planarizing surface. The endpoint can accordingly be accurately achieved by noting the exposure of the polish-stop layer. Therefore, several embodiments of the planarizing machine 100 and methods described above with reference to Figures 2-3D not only form a planar surface at an accurate endpoint, but they do so in a manner that reduces the overall time for a planarizing cycle to enhance the throughput of planarized workpieces.

[0028] Figure 4 is a schematic view of a planarizing machine 400 in accordance with another embodiment of the invention. The planarizing machine 400 has several similar components to the planarizing machine 100 described above with reference to Figure 2, and thus like reference numbers refer to like components in Figures 2 and 4. In addition to the components of the planarizing machine 100 shown in Figure 2, the planarizing machine 400 includes a conditioner system 180 and a pad monitor 190. The conditioner system 180 can include a drive system 182, an arm 184 coupled to the drive system 182, and an end effector 186 carried by the arm 184. The end effector 186 roughens or otherwise alters the planarizing surfaces 142a or 142b to impart the desired surface condition to the pads 140a-b.

[0029] The planarizing machine 400 provides the desired surface roughness or other condition to the planarizing surfaces 142a-b. In general, the computer 170 controls the drive system 182 to selectively press the end effector 186 against the pads 140a-b. The time, downforce, movement and end-effector type can be selected to produce a desired surface condition on the pads 140a-b. For example, a higher downforce can be used to provide a rougher surface on the pads. The computer 170 can accordingly cause the drive system 182 to press the end effector 186 against the first planarizing surface 142a at one downforce and then press the end effector 186 against the second planarizing surface 142b at a lower downforce so that the first roughness of the first surface 142a is greater than the second roughness of the second surface 142b. The pad monitor 190 for each pad can include a sensor 192 that provides an indication of the surface condition of the planarizing surfaces 142a-b. The sensor 192 can be a stylus that measures the profile of the planarizing surfaces 142a-b, or the sensor 192 can be an optical sensor that optically determines the roughness or other surface condition of the pads 140a-b.

[0030] The planarizing machine 400 can perform a method in which the conditioning system 180 conditions the first pad 140a such that the first planarizing surface 142a has the first roughness, and then condition the second

pad 140b so that the second planarizing surface 142b has the second roughness. The particular downforce that is used to impart the first and second roughnesses to the pads 140a-b can be determined by the pad monitors 190. For example, if the pad monitor 190 for the first pad 140a notes that the first surface 142a has a roughness within a desired range for the first roughness, then it can indicate that the conditioning system 180 does not need to condition the first pad 140a. On the other hand, if the pad monitor 190 indicates that the first planarizing surface 142a is substantially smooth, then it can set the downforce of the conditioning system 180 at a relatively high downforce level to impart the desired roughness to the first planarizing surface 142a. It will be appreciated that the conditioning system 180 can condition the entire planarizing surface of each pad 140a-140b according to the desired roughnesses, or that only selected regions identified by the pad monitors as being outside of a desired roughness can be conditioned by the conditioning system 180.

[0031] Figure 5 illustrates a planarizing machine 500 in accordance with another embodiment of the invention. In this embodiment, the planarizing machine 500 includes several components that are substantially similar to the planarizing machine 400 described above with reference to Figure 4, but the planarizing machine 500 only includes a single plate 120 and a single pad 140. The pad 140 has a planarizing surface 142 that can be changed from a first planarizing surface having a first roughness to a second planarizing surface having a second roughness by the conditioning system 180. For example, the conditioning system 180 can press the end effector 186 against the planarizing surface 142 at a relatively high downforce to form a first planarizing surface having the first roughness. The carrier system 150 can then press the workpiece 160 against the first planarizing surface and an abrasive slurry during a first abrasive stage of the planarizing cycle. After the surface of the workpiece has become at least substantially planar as shown above with reference to Figure 3B, the conditioning system 180 can re-condition the planarizing surface 142 so that it is smoother and has a second roughness less than the first roughness. The reconditioned

planarizing surface of the pad 140 can define the second planarizing surface. The carrier system 150 can accordingly press the workpiece 160 against the second planarizing surface in a second abrasive stage of the planarizing cycle. As a result, the workpiece 160 can initially be planarized against a rough planarizing surface during the first abrasive stage to remove topography from the surface of the workpiece 160, the pad 140 can be conditioned to provide a smoother planarizing surface, and then the smoother second planarizing surface of the same pad 140 can be used to remove the overburden region *O* of the fill layer at a faster polishing rate to reach the final endpoint.

[0032] From the foregoing, it will be appreciated that specific embodiments of the invention have been described herein for purposes of illustration, but that various modifications may be made without deviating from the spirit and scope of the invention. For example, the plates 120 can be stationary and the current monitor can be coupled to the drive system for the workpiece carrier to detect the onset of planarity and the endpoint. Accordingly, the invention is not limited except as by the appended claims.